Statistical analysis of fiber gripping effects on Kolsky bar test[1]

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ABSTRACT

Preliminary data for testing fibers at high strain rates using the Kolsky bar test by Ming Cheng et al. [1] indicated minimal effect of strain rate on the tensile stress-strain behavior of PPTA, poly (p-phenylene terephathalamide) fibers. In a different study, Lim et al.[2] reported that the tensile strengths of the copolymer aramid fibers are strain rate dependent. Usually with single fiber tests, a large sample population is needed to get statistically significant results. To date with high strain rate tests, technical issues associated with specimen preparation appear to limit the number of samples that can be tested within a reasonable time. In this study, the authors investigate the feasibility of a new gripping design in order to ultimately establish a reliable, reproducible, and accurate Kolsky bar test methodology for single fiber tensile testing with high throughput. Preliminary results performed under a quasi-static strain rate with 5 mm and 60 mm gauge lengths showed that the PPTA fibers are gauge length dependent. This gripping and size effect must be considered in determining the true strain rate effect on fiber strength.

1. INTRODUCTION

Although the material properties of high performance fibers are routinely characterized quasi-statically, two recent workshops have underscored the need to obtain accurate and reproducible high strain rate (HSR) test data on these fibers to ensure their ballistic performance in lightweight soft body armor (SBA) applications [3,4].In a previous publication [5], it was noted that the Kolsky bar technique, which requires test specimens less than 10 mm, offers promise as a measurement tool for providing these critical data. It was also highlighted that the increased percentage of perturbed gauge length in short fibers relative to long fibers and the wicking of the glue along the length of the fiber that is often used to attach the fiber specimen to the Kolsky bar can create measurement challenges by rendering the fiber gauge length unknown. In addition, the gluing approach has been found to be time consuming, yielding a couple of tested samples per day.

In our initial publication [5], quasi-static tests on 2 mm and 60 mm long guage length samples were performed using two different gripping methods. In gripping method 1, the fiber is glued to a template of known gauge length, while in gripping method 2, the fibers are directly gripped between two tension-controlled polymethyl methacrylate (PMMA) blocks. The data were initially analyzed by the Stoner et al [6], and Newel et al.[7] grip effects model that account for failures caused by end effects. In both gripping techniques, this model only adequately predicted the survival behavior at the 60 mm gauge length and was found to be a poor predictor of the survival behavior at the 2 mm gauge length.

Although the grip effects model was found to be of minimal value, the survival results indicate that the failure behavior of the fiber may be changing with shorter gauge lengths. In this study, a detailed statistical analysis of the failure data at 60 mm and 5 mm gauge lengths are evaluated using the direct gripping method under quasi-static loading conditions to provide a basis for assessing the fidelity of HSR data using the Kolsky bar.

2. EXPERIMENTAL PROCEDURE

2.1 Quasi-static loading

For the tensile test under quasi-static loading, poly (p-phenylene terephthalamide) fibers (PPTA) and the Favimat testing machine (Textechno Herbert Stein GmbH & Co. KG.[2]) were used. A fiber gripping technique (direct grip) was used and is shown in Figure 1. While the fiber is under slight pre-tension by 0.1 g of the deadmass to maintain the straightness and alignment to the grips, a single PPTA fiber is directly clamped between two blocks on both ends and the clamping force of the blocks is controlled by tightening a spring. The gauge lengths of the fiber specimens were 5 mm and 60 mm. The lengths were chosen to investigate the length dependency of the fiber under the quasi-static loading condition. The tensile tests were performed under the constant strain rate 0.00056 s^{-1} by using a commercial single fiber testing machine with uncertainty in the load cell of 0.1 %. Fiber diameters were measured using the optical microscope on a five different places and the average value was used for the strength calculation.

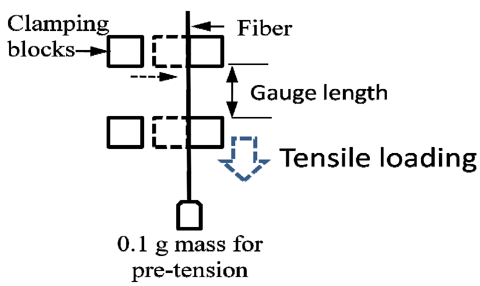

Figure 1. Schematic and closed up of the direct grip for quasi-static loading

Statistical analysis

For this paper, we followed the analysis used by Holmes et al. [8] Briefly, skewness and kurtosis ratios should give an indication of the normality of the fiber failure strengths and it is important to know if the distribution changes as the gauge length changes for 60 mm to 5 mm. The skewness measures the deviation from symmetry of a distribution, and the kurtosis measures the peakedness of a distribution (i.e. the center, or peak, much shorter or taller than that of a normal distribution?). Normality of the distribution is typically rejected if the ratio of either statistics to its standard error is less than – or greater than +2 [8,9]. In addition, ANOVA (Analysis of Variance) was carried out for the failure loads, diameters and strengths for both gauge lengths to investigate the change of the data as the fiber gauge length changes.

[2] Certain commercial materials and equipment are identified in this paper to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply necessarily that the product is the best available for the purpose.

RESULTS AND DISCUSSION

The test results are presented in Table 1 with the skewness and the kurtosis of the strength data. The average failure load measured at the 5 mm gauge length is greater than that for the 60 mm gauge length with a P-value of 0.006, while the average diameters between two gauge lengths are similar with the P-value of 0.470. The average tensile strength for the 5 mm gauge length is greater than for the 60 mm length with the P-value of 0.002, which shows the gauge length dependency of the tensile strength.

Since fiber strengths are typically applied for ballistic fiber researches, the normality investigation for the fiber strength data has been carried out as mentioned earlier. Summary statistics of Table 1 and the histogram in Figure 1 for the tensile strengths with the 5 mm gauge length show the deviation from normality, but the non-normality disappears after the single lowest data point shown at left tail region of Figure 1 (i.e. 1.55 GPa) removed from the strength data. By removing the single outlier, the skewness and kurtosis ratio of the strength data with the 5 mm gauge length in Table 1 change to -1.87 and 0.69 respectively indicating the normality of data, and the histogram shown in Figure 2 fits with the normal distribution. The distribution of the strengths with the 60 mm gauge length is almost on the limit of the normal distribution showing -2.05 for the skewness ratio, which appears to be acceptable for the normality check. The histogram of the strength data with the 60 mm gauge length is shown in Figure 3 and slightly skewed to the lower tail as indicated in the skewness ratio.

Table 1. Summary statistics for the histograms in Figure 1

Gauge length (mm)	Load (N)	Diameter (μm)	Strength (GPa)	Skewness ratio [Skewness statistic/Std. error]	Kurtosis ratio [Kurtosis statistic/Std. error]
5	0.39±0.06	13.29±0.70	2.79±0.38	-3.12, (-1.87*)	2.60, (0.69*)
60	0.35±0.06	13.37±0.57	2.53±0.44	-2.05	-0.35

*refers the skewness and kurtosis ratios after removing single outlier from strength data.

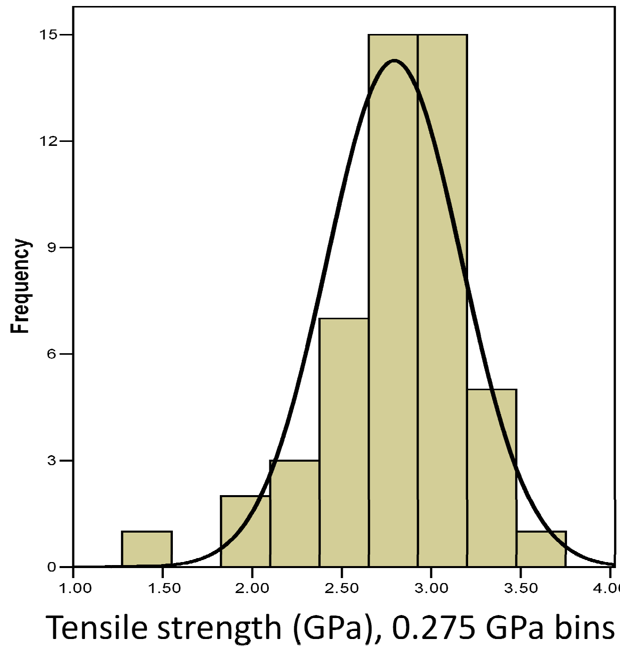

Figure 1 Histogram of the tensile strength for the 5 mm gauge length tests.

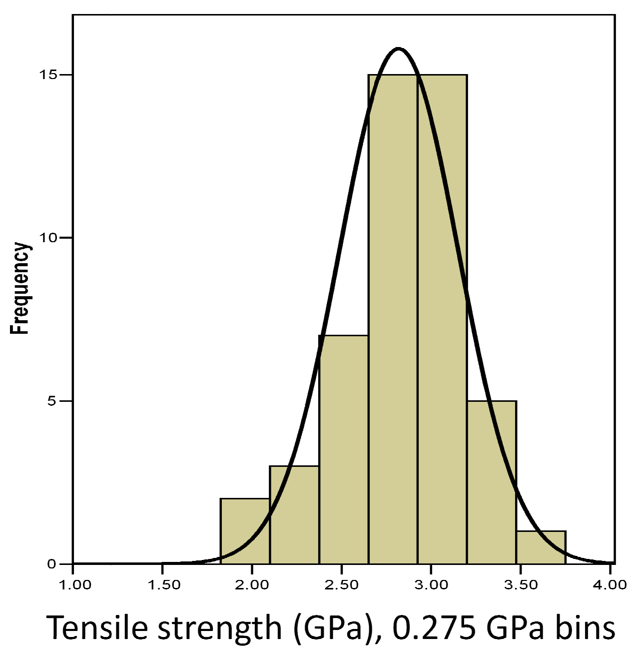

Figure 2 Histogram of the tensile strength for the 5 mm gauge length tests after removing the single outlier.

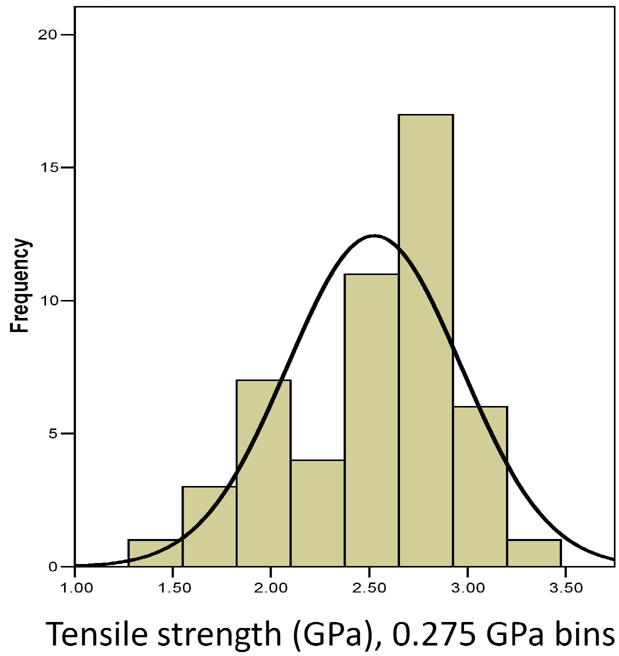

Figure 3 Histogram of the tensile strength for the 60 mm gauge length tests.

The 2-parameter Weibull analysis [10] is often used to address the statistical distribution of the fiber strength. Typically the shape parameter relates to the shape of the data distribution, and a higher parameter value corresponds to a narrow data distribution. The scale parameter decides the fitting position of the data on the Weibull distribution. the position A detailed discussion can be found elsewhere [11]. A Weibull analysis was done to determine the strength distribution of the fibers as a function of the gauge lengths.

Table 1. Physical properties of the PPTA fibers and Weibull parameters of the fiber strengths measured under the quasi static loading condition

Gauge length (mm)	Scale parameter (GPa)	Shape parameter	PPCC
5	3.49	9.50	0.98
60	4.74	7.29	0.99

3. CONCLUSIONS

Fiber tensile tests using a direct fiber grip technique have been carried out under quasi-static loading conditions to ascertain the feasibility of this fiber gripping method for possible use for the HSR testing with the Kolsky bar. A goal was to look at the normality of fiber failure (i.e. strength) as the gauge lengths were decreased from 60 mm to 5 mm. This answers the question whether this gripping method creates any damage on the fiber and causes non-normal distribution of the failure. Based on the test results, it was shown that the normality of the fiber strengths was maintained for both 5 mm and 60 mm cases. This indicates that the gripping effect using the direct grip was the same at the 5 mm and 60 mm cases, and these results support applying the direct grip for the HSR test.

Under the quasi-static test, the average fiber tensile strength with the 5 mm gauge length was higher than the 60 mm. This indicates that the fiber tensile strengths in this study depend on the gauge length and the length dependency of the fiber strength must be considered for determining the true strain rate effect of the fiber.

Based on two results from the normality of the strength data and the length effect on the strength, a gripping effect of the direct fiber grip used in this study appears to be negligible. Therefore, it is concluded that the direct fiber grip can be applied for the high strain rate test using the Kolsky bar.

References

1. Cheng, M., Chen, W. N., & Weerasooriya, T. "Mechanical properties of Kevlar (R) KM2 single fiber." *Journal of Engineering Materials and Technology-Transactions of the Asme* 127 (2005): 197-203.

2. Lim, J., Zheng, J. Q., Masters, K., & Chen, W. N. W. "Mechanical behavior of A265 single fibers." *Journal of Materials Science* 45 (2010): 652-661.

3. "NIST Technical workshop on research and metrology of ballistic fibers". In: 2007.

4. "Multiscale materials behavior in ultra-high loading rate environments, US Army research laboratory workshop". In: 2008.

5. Jae Hyun Kim, Richard.L.Rhorer, Haruki Kobayashi, Walter G.McDonough, & Gale A.Holmes. "Effects of fiber gripping methods on single fiber tensile test using Kolsky bar". In: 2010.

6. Stoner, E. G., Edie, D. D., & Durham, S. D. "An End-Effect Model for the Single-Filament Tensile Test." *Journal of Materials Science* 29 (1994): 6561-6574.

7. Newell, J. A. , Sagendorf, M. T. "Experimental verification of the end-effect Weibull model as a predictor of the tensile strength of Kevlar-29 (poly p-phenyleneterephthalamide) fibres at different gauge lengths." *High Performance Polymers* 11 (1999): 297-305.

8. Holmes, G. A., Peterson, R. C., Hunston, D. L., & McDonough, W. G. "E-glass/DGEBA/m-PDA single fiber composites: The effect of strain rate on interfacial shear strength measurements." *Polymer Composites* 21 (2000): 450-465.

9. *SPSS Bse 8.0 Application Guide, pp. 27-28, SPSS Inc., Chicago (1998)*. 1998.

10. Weibull, W. "A Statistical Distribution Function of Wide Applicability." *Journal of Applied Mechanics-Transactions of the Asme* 18 (1951): 293-297.

11. Gurvich, M. R., DiBenedetto, A. T., & Ranade, S. V. "A new statistical distribution for characterizing the random strength of brittle materials." *Journal of Materials Science* 32 (1997): 2559-2564.